Study of Seismically Induced Landslide Zones, Related to Chamoli Earthquake of 1999, Garhwal Himalaya, India

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ABSTRACT

Landslides are very common in the seismically prone areas of the Garhwal Himalaya. A seismic activity involves displacement either in vertical or horizontal direction and such displacements create slope failure by mass wastings. The maximum impact of Chamoli earthquake was experienced, in the zones of intersection of tear faults with the Main Central Thrust (MCT). During this earthquake, large-scale landslides and subsidence caused destruction of many villages located over the hillside slopes. On the basis of field survey, pre and post earthquake IRS 1C/1D (LISS III/PAN) images, more than 100 landslides have been identified in addition to the reactivation of 17 old landslide zones. Rockfalls, rock avalanches, slump failure, rock and soil slides are common forms of mass wasting. The ground motions induced on the earthquake have acted as a triggering force for causing the slope failures. This earthquake has produced a lot of fissures at the rocks and land surfaces, which were traced upto 500 m treading NW-SE with a down throw upto 10 inches. Most forms of the landslide get triggered when the limiting thresholds for slope failures are exceeded.

INTRODUCTION

There is hardly any part of the Himalaya, which is really free from from landslides. A perusal of the slope failures has indicated that, the factors primarily responsible for their generation are (i) the slope inclination (ii) slope height (iii) lithological and structural characteristics and (iv) landuse pattern. The ground motions induced by the earthquake appear to have acted as a triggering force in causing the slope failures. Earthquakes have caused landslides almost every year in seismically active zones in the world and claimed disruption of the communication links, loss of the property and human lives. The landslide disasters were relatively small in comparison with the heavy damages to man-made constructions such as roads, high buildings, bridges, etc.

Prediction of earthquake induced landslide includes time, site and magnitude. Time prediction is related to earthquake predictions. Whereas site and magnitude predictions are geotechnical problems. The purpose of the prediction of landslide on natural slopes are not only protection of slopes, but the prevention of damages to people and houses built in the landslides prone slope areas. The methods of geotechnical prediction of earthquake induced landslides, namely seismic stability analysis are classified in various ways according the basis for its predictions as given below:

1. Prediction based on the peak strength of bedrocks.
2. Prediction based on the displacement
3. Prediction based on the steady state strength
4. Prediction based on the apparent friction angle during motion

It is believed that the long run-out rapid landslides cause catastrophic disasters, while slow and short moving landslides cause only limited disasters. Identification of slopes which may cause catastrophic landslides during earthquakes can be made from (1) slopes containing usually a saturated layer, (2) soils susceptible to mass liquefaction or surface liquefaction and (3) existence of houses within the unstable areas. In addition the prediction of such dangerous landslides should also be based on he apparent friction angles during the motion

SEISMICITY OF GARHWAL REGION

It is well known that the Himalayan mountain system is a product of collision between the Indian and the Eurasian plates, which began at about 50-55 Ma and is still continuing. The convergence rate between the two plates is of the order of 50 mm/yr at present (Minster and Jordan, 1978). Very high elevation of the mountains may be attributed to the uplift of the rock formations due to thrust movements directed from north to south along the Main Central Thrust (MCT) and the Main Boundary Fault/ Thrust (MBF/MBT). The rapid rate of convergence between the Indian and the Eurasian plates is evidenced by high seismicity associated with MBT and MCT. Four major earthquakes exceeding magnitude (Ms) > 8.4 have taken place along the Indian plate margin, along the Himalayan arc (Richter, 1958; Seeber & Armbruster, 1981).

On the basis of manifestations of neotectonic activities, direction of crustal shortening as evidenced in Quaternary sediments, the source mechanism of discrete seismic events and seismicity patterns, Narula (1991) displayed a concentration of seismic events at different locales in Garhwal and Kumaun Himalaya. Most of the events are located in the vicinity of the surface trace of MCT while in the Himachal area; the seismicity is concentrated between the MCT and MBT. Based on several features like seismicity patterns, focal mechanism studies, geophysical attributes, tectonics flux studies of pattern of geothermal manifestations, Narula (1992) divided the main longitudinal Himalayan seismic zone into discrete seismotectonic segments with well defined transverse boundaries marked by interpretative fundamental faults. Their segments are the Kashmir block; Chamba-Kishtwar block; Kangra block; Shimla block; Garhwal block and Kumaun block. It has been contended that the segmentation of the crust by transverse feature might result in the block specific adjustment of mechanical strain and these blocks would respond to the discrete stress fields and would thus rupture individually. These segmentation boundaries are the result of first order interpretation and it is possible that the individual blocks could have additional sub-parallel transverse features below the metasedimentary wedge overlying the basement. Narula and Shome (1992) have suggested that the transverse features have a significant role in the generation and modification of source parameters. Acharyya & Narula (1998) also contented that segmentation boundaries might act as earthquake nucleation sites with rupture propagation only in one direction along the longitudinal seismic source (Himalayan trend).

The Garhwal – Kumaun sector of Himalaya is known for high levels of seismic activities. Thirteen earthquakes of $M \geq 6$ have occurred in Garhwal – Kumaun area in the last 97 years (table 1). This indicates that on an average strong earthquakes seem to occur every 8 years or so, in this area. A study of the mechanism of these earthquakes indicates the impact of thrusting from north with NNE compression. Before the Chamoli earthquake of March 1999, this domain was struck by the Uttarkashi earthquake of magnitude 6.6 mb on the 20th October 1991, which took a toll of 768 human lives and caused extensive damages. The Chamoli earthquake of 29th March, 1999 measuring 6.8 (mb) with epicenters at Lat 30.41^{o}N and Long 79.42^{o}E is located at about 80 km east of Uttarkashi in a similar geotectonic setting. This earthquake, though of a large magnitude, has caused less damage than those caused by the Uttarkashi earthquake. The maximum acceleration in the Chamoli area was estimated at 0.2 g and the recorded acceleration at Tehri (where the controversial Tehri dam is located, was 0.05g. Numerous aftershocks occurred also within the intensity VIII area. The largest after-shock of mb 5.3 occurred one hour after the main shock. Other 30 aftershocks occurred on 13.3.1999, and the second largest shock occurred on 31.3.1999. The loss of life during this event was put at 103 and the number of people injured was 395. A total of 4495 houses have suffered very heavy damages including the collapse of walls built with assorted rubble in mud mortar and more than 25,000 houses have partially been damaged. Major terrain changes like generation of landslides, development of fissures, emergence of new springs etc. have taken place in an approximate area of 1800 sq.km. in the districts of Chamoli, Rudraprayag and Tehri.

Table 1. Earthquake of $M \geq 6.0$ in Garhwal - Kumaun region

Date	Mag.	Lat. N	Long. E
Sep. 1, 1803	8.0	30.300	78.800
May 26, 1816	6.5	30.900	79.000
June 6, 1902	6.0	31.000	79.000
Oct. 14, 1911	6.8	31.000	80.500
Aug. 28, 1916	7.7	30.000	81.000
July 27, 1926	6.0	30.400	80.400
Oct. 8, 1927	6.0	30.500	80.500
March 5, 1935	6.0	29.700	80.200
June 4, 1945	6.5	30.000	80.000
Dec. 28, 1958	6.2	29.500	80.000
Dec. 31, 1958	6.0	30.100	80.700
Sep. 26, 1964	6.2	29.600	80.900
June 27, 1966	6.0	29.600	80.900
Oct. 19, 1991	6.4	30.780	78.770
March 29, 1999	6.8	30.550	79.424

EARTHQUAKE INDUCED LANDSLIDES

There are numerous examples of landslides triggered on earthquake. The Assam Earthquake of 1950 caused landsliding of over 15000 km^2 of the eastern Himalaya, involving an estimated total displacement of 50 billion m^3 of material due to tens of hundreds of landslides (Kingdon, 1955). The Uttarkashi, 1991 earthquake and its after shocks caused over 200 large and several hundred smaller landslides.

A majority of the major landslides are confined within isoseismal VIII.

Chamoli 1999, earthquake triggered more than 100 landslides in addition to the reactivation of 17 old slide zones. The first case of earthquake induced rockslide along Badrinath highway was witnessed 3 km before Nandprayag (at Sonta) within jointed quartzite. At Nandprayag, the terrace slopes show a slump failure and generation of resultant tensional cracks. The frequency of slides and fissures increases as one proceeds towards Chamoli town in the Alaknanda valley. In the Birahi Ganga valley upto Gohna, the coseismic slope failures were so pronounced that a thick dust, generated out of the slide zone had settled all over the place. The area around Ghingriyan and its adjacent villages is marked by a very active and prominent debris slide developed in loose morainic deposits, which have endangered the nearby villages. The Chamoli – Badrinath road is breached at several places in this active zone. The most prominent of the rockslides occur 2 km to the west of Gopeshwar town on a prominent quartzite ridge. Similar blockades were also seen in the sector of Gopeshwar – Pokhri and Chamoli – Gopeshwar roads. In the Mandakini valley, the Chandrapuri – Mohankhal sectors has experienced a number of rock failures that have affected some of the villages enroute as well. Wedge failure also has been observed just before Rudraprayag on the thickly bedded quartzite and between Mandal – Gopeshwar road. Wedge failure leading to rockfall and remobilization of Quaternary deposits leading to debris fall are the main landslide types developed on earthquake. Rock falls have also occurred due to brittle failure along the joints and fractures. It is interesting to note that a cluster of 18 major slide zones has developed between Bhatwari – Akhori area, in the vicinity of a WNW-ESE trending tectonic alignment. The ground motions induced by the earthquake have acted as a triggering force in causing the slope failures. External factors such as ridges, convex hills and escarpments have modified the influence zone.

A very peculiar feature of this earthquake was that it has produced lot of land fissures over the rocks and landsurface. The landfissure was traced upto 500 mts trending NW-SE with a down throw of 10 inches. This land fissures show a clear cut thrust faulting with a footwall movement towards SW and hanging wall towards NE was raised to 10 inches. This one-meter deep crack was reported in Gurpunga village in the crystalline micaceous schists. Prominent ground fissures, produced as a result of stress in the steep slope mass, was witnessed at Makku Maikhet – Indranagar, i.e 40 km west of Chamoli, very prominent fissures on road surface and a slight tilt of dwellings were witnessed. In the area between Pipalkoti and Helong covering villages of Tangri, Garurganga, Pakhi, Helang, Belakuchi etc. large ground fissures and cracks ranging in thickness from 1 cm to 50 cm and extending for a few meters to 500 meters were recorded in the vicinity of the MCT. Cracks ranging from 5 m to 500 m in length, 3 cm to 12 cm in width and with 5 cm to 25 cm vertical displacements have adversely affected the slope stability of the region. These cracks are approximately 0.5 to 2.5 m deep and are oriented in NW-SE, NNW-SSE, N-S and E-W directions, however the prominent direction is NW-SE. The widening of the cracks and vertical displacements have been observed along he free faces of slopes composed of Quaternary deposits. Percolation of rainwater along these cracks creates landslides during monsoon.

In cases, where the rocks dip in a direction opposite to the surface slope such movements have resulted in ground subsidence and landslides that are attributed to widening of the joints. Thus movement is essentially controlled by gravity. In the cases, where dip of the rock mass and the surface slopes have same direction, planar and wedge failures were observed. In isolated cases, particularly near scarp faces, the ground cracks are related to the displacement of large rock blocks or wedges along preexisting fracture planes.

CAUSES OF LANDSLIDE TRIGGERED BY EARTHQUAKES

In a majority of cases, landslides take place due to the earthquake shock, and a few of them may also occur hours and days after the shock. According to Keefer (1984), rockfalls, rock avalanches, rockslides and soilslides are the commonest forms of landslides, which get triggered when the limiting thresholds for slope failures get exceeded. Threshold conditions of various types of seismically generated mass movements and their relative abundance are presented (table 2). Keefer believed that the extent of area within which landsliding is generated tends to increase with the shock magnitude, from less than 100 km^2 at magnitude 4, to about 5,00,000 km^2 at magnitude of 9.2.

Oldham (1899) while reporting on the 1897 Assam earthquake provided a very simple model to explain earthquake triggered landslides. He considered the section of a simple slope, covered by a soil mass which derived its stability through friction between itself and underlying rocks. When the underlying rock is set into motion by the shock waves of an earthquake, the surfacial portion of rock will, at one period of the shock or the other, acquire outward motion. This motion will get communicated to the soil cover. In the next semi-phase of the wave, the movement of surface of the rock will be inwards, but the inertia of the overlying soil cover will prevent the soil to respond instability, and the consequence would be more or less complete loss of pressure of the soil cap over the rock. This reduction of pressure means a reduction of friction, which alone prevents the soil cap from sliding down the hills, and thus a landslip takes place, where the reduction of resistance and the slopes of hill are sufficient to allow it. That is how the threshold for slope failure is exceeded and a landslide follows.

Table 2 Threshold condition of various types of seismically generated mass movement and their relative abundance (Keefer, 1984)

A	B	C	D	E
Rockfalls	4.0	VI	IV	$>10^5$
Rock slides	4.0	VII	V	$>10^5$
Disrupted soilslides	4.0	VI	IV	$>10^5$
Soil falls	4.6	VI	IV	10^3-10^4
Soil-block slides	4.5	VII	V	10^2-10^3
Soil slumps	4.5	VII	V	10^4-10^5
Soil-lateral spreads	5.0	VII	V	10^4-10^5
Rock slumps	5.0	VII	V	10^3-10^4
Rapid-soil flows	5.0	VII	V	10^3-10^4
Rock-block slides	5.0	VII	V	10^3-10^4
Slow-earth flows	5.0	VII	V	10^2-10^3
Subaqueous slides	5.0	-	-	10^2-10^3
Rock debris avalanches	6.0	VI	IV	10^2-10^3
Soil avalanches	6.5	VI	IV	10^2-10^3

(A) Types of mass movement (Varnes, 1978); (B) Threshold earthquake magnitude; (C) Common threshold scale MM intensity; (D) Minimum threshold scale MM intensity; (E) Abundance in 40 documented earthquakes

CONCLUSION

Earthquake induced first time landslides are few but earthquake triggered landslides are many. Some Indian and Foreign earth scientists have postulated that a huge or giant earthquake of M>8 or even larger that 8.5 could occur on the one of the two major thrusts in the Central Himalaya, possibly in UP Himalaya. If such a larger earthquake occurs, than definitely thousands of landslides will take place, which will cause heavy damage to life and property. It is surprising that at present little concern is shown towards protection of housing, community buildings, temples and monuments which have not been provided any earthquake resistance features at all and the collapse of which in such a calamitous earthquake occurrence, could lead to loss of a hundred thousands lives. It is high time that an appropriate damage scenario is worked out and people warned of the consequences of such a prediction coming true.

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